Model projections of atmospheric steering of Sandy-like superstorms

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Superstorm Sandy ravaged the eastern seaboard of the United States, costing a great number of lives and billions of dollars in damage. Whether events like Sandy will become more frequent as anthropogenic greenhouse gases continue to increase remains an open and complex question. Here we consider whether the persistent large-scale atmospheric patterns that steered Sandy onto the coast will become more frequent in the coming decades. Using the Coupled Model Intercomparison Project, phase 5 multi-model ensemble, we demonstrate that climate models consistently project a decrease in the frequency and persistence of the westward flow that led to Sandy's unprecedented track, implying that future atmospheric conditions are less likely than at present to propel storms westward into the coast.

climate change | Hurricane Sandy | global climate models | blocking

Recently there has been a lot of focus in the popular media on whether frequent extreme storms over the United States are becoming the "new normal," and whether anthropogenically forced climate warming is the cause. In fact, some recent scientific papers have alluded to this possibility and have implicated the recent accelerated warming over the Arctic as the cause of the landfall of Sandy on the New Jersey coast in 2012. We show that current state-of-the-art climate models project that increasing greenhouse gases will decrease the frequency of occurrence of the atmospheric circulation patterns that propelled Sandy into the East Coast of the United States, with the flow being more likely than at present to propel tropical storms into the Atlantic Ocean.

Of all of the attributes of Hurricane and then Post-Tropical Storm Sandy, arguably the most anomalous was its westward track. The near-perpendicular angle at which Sandy hit the New Jersey coast likely contributed to the large storm surge north of the landfall point, including in New York harbor. Sandy's direct approach from the east, rather than from the south, kept the storm from weakening from interaction with land. In addition, although a number of factors contributed to the magnitude of the storm surge along the New York–New Jersey coast, the positioning of most of New York and most of New Jersey on the right side of the track, where the storm's translational motion was superposed constructively on its rotational flow, likely contributed to the surge.

Using a stochastic model, Hall and Sobel (1) estimate that the return period of a category 1 or greater storm with a landfalling track at an angle as large as Sandy's on the New Jersey coast is 700 y (95% confidence interval 400–1,400 y) in the present and recent-historical climate, not accounting for climate change. [Other studies (2, 3) derive return periods in the 400- to 800-y range for a tropical cyclone with a surge of the magnitude of Sandy's in New York harbor; the surge is related to multiple factors, of which the incidence angle of the track on the coast is only one.] This allows for two possibilities: either Sandy was simply an extremely rare event, or climate change has increased the odds so that the return period reported by Hall and Sobel (1) is an overestimate. We address the latter question here by focusing on how the frequency of the large-scale flow patterns that gave Sandy its anomalous path will change in a warming climate.

More precisely, we focus on three aspects of the atmospheric circulation that potentially contributed to Sandy's unprecedented track: (*i*) an equatorward-shifted Atlantic midlatitude jet stream (Fig. 1*A*), (*ii*) a blocking anticyclone over the Atlantic (Fig. 1*B*), and (*iii*) a large-scale, cyclonic (counter-clockwise) Rossby wave-breaking event off of the coast (Fig. 1*C*). These three atmospheric features often occur simultaneously over the North Atlantic, and all three were present over the Western Atlantic Ocean basin preceding Sandy. We briefly discuss each below.

First, during the last 2 weeks of October 2012, the jet stream was shifted significantly equatorward of its typical latitude, quantified by a negative North Atlantic Oscillation (NAO) index of −1.5 standard deviations (4). At the time of Sandy's landfall (approximately 1:00 AM Greenwich Mean Time on October 30, 2012), the winds were easterly (east to west; negative) over the northeast United States, as shown by blue shading in Fig. 1*A*, with the westerly jet stream split to the north and south (red shading). Typically, the steering-level winds over this region are westerly (i.e., from west to east; positive) as shown by the black contours in Fig. 1*A*; such westerly winds usually advect tropical storms northeastward (i.e., away from the coast) as they enter the midlatitudes (Fig. 1*D*). However, the anomalous easterlies during Sandy steered the storm onshore, giving it the most perpendicular track into the coast of any tropical cyclone in the historical record along this section of the US coast (1).

Second, a blocking anticyclone was also present over the mid-Atlantic at the time of Sandy's landfall, as seen in the 500-hPa geopotential height field (Fig. 1*B*). Blocking over the Atlantic is strongly tied to the NAO, with higher blocking frequencies under negative NAO conditions when blocks divert the zonal flow to the south, typically persisting for a week or more (5). Such persistent flows provide the conditions for extreme surface weather and have been implicated in summer heat waves (6–8) and winter cold air outbreaks (9).

Third, persistent blocks over the West Atlantic are nearly always preceded by cyclonic Rossby wave-breaking events, which act to set up the blocking anticyclone (10). Such Rossby waves propagate on the vorticity gradient, owing in part to the rotating earth, and the momentum fluxes from the breaking of these waves (much like the breaking of an ocean wave) are an integral part of what drives the midlatitude atmospheric jet stream. Fig. 1*C* shows that such a cyclonic wave-breaking event was present when Sandy made landfall, with the path of Sandy (shown by the white circles) largely following the anomalously cyclonic (positive) vorticity contour.

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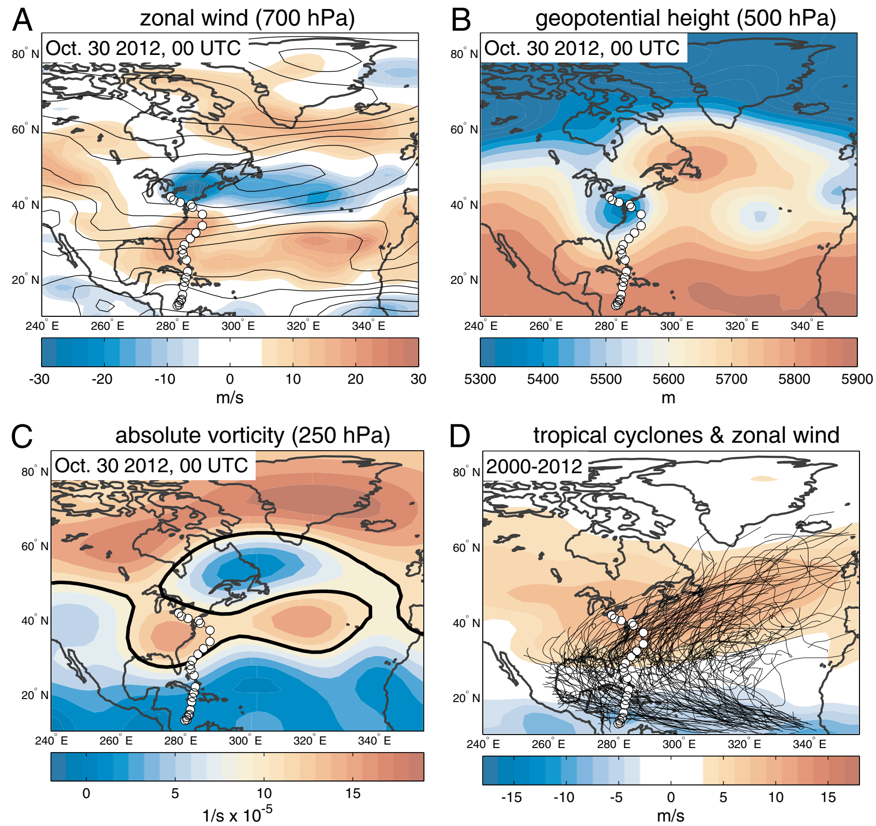

Fig. 1. (*A*–*C*) October 20, 2012 (*A*) 700-hPa zonal wind, (*B*) 500-hPa geopotential height field, and (*C*) 250-hPa absolute vorticity field. Meteorological fields are from the NCEP/NCAR Reanalysis (National Centers for Environmental Prediction/National Center for Atmospheric Research). (*D*) Tropical cyclone tracks from the National Hurricane Center HURDAT2 data and mean 700-hPa zonal winds over 2000–2012. Thin black contours in *A* denote the October climatology between 2000 and 2012. The thick black contour in *C* signifies the 11×10^{-5} s^{-1} overturning contour associated with a cyclonic Rossby wave-breaking event. The white circles denote the track of Sandy.

Given that these unusual atmospheric conditions were crucial to steer Sandy, the obvious question is: will these conditions change in the future? In other words, will changes in the large-scale flow patterns make westward steering of transitioning Atlantic tropical cyclones more likely, thus increasing the probability of landfall of any such storms whose tracks bring them near the coast of the northeast United States?

The global climate models that participated in the Coupled Model Intercomparison Project, phase 5 (CMIP5) offer an ensemble-based approach to assessing how the atmosphere will respond to increasing greenhouse gas concentrations. We document here how the frequency of the atmospheric flow conditions present during Sandy are projected to change in the future, by analyzing the differences between the simulated present-day (Historical; 1980–2000) and future [Representative Concentration Pathway (RCP) 8.5; 2076–2099] climate scenarios from the CMIP5 multimodel ensemble. RCP8.5 is an extreme climate forcing scenario, with global carbon dioxide emissions quadrupling by 2100 compared with 2000 (details in *Materials and Methods*). We use this scenario, as opposed to a more conservative one, for two reasons: first, this scenario will provide an upper bound on the atmospheric changes projected by the models, and second, a larger warming signal often provides a better signal-to-noise ratio, allowing us to distinguish natural variability from the effects of anthropogenic emissions.

Because the easterlies in the lower troposphere ultimately steered Sandy into the East Coast, we start by examining these. The CMIP5 models robustly project that in the North Atlantic the frequency of strong easterlies (less than −10 m/s) at 850 hPa will decrease during the August–October (ASO) season by 2100 (Fig. 2). Using deeper atmospheric layers does not change the conclusions (analysis on other pressure surfaces and for a cutoff of −5 m/s is shown in Fig. S1). We focus on the ASO period because this is the season with the highest frequency of Atlantic tropical cyclones that undergo extratropical transition (11), a process whereby the tropical storm evolves into an intensifying midlatitude cyclone as it moves into midlatitudes (12). Sandy underwent such a transition as it moved northward.

The black contours in Fig. 2 show the easterly component of the zonal winds averaged over October 27–29, 2012. The maximum off of the New Jersey coast is associated with Hurricane Sandy itself, but the large-scale easterlies off of Newfoundland that extend into the Atlantic Ocean are associated with the Rossby wave-breaking event and the concurrent blocking-high south of Greenland. Note that we average over several days before Sandy's landfall because Sandy itself modifies the flow, and we wish to determine the importance of the background state on tropical storm paths. The models project a broad decrease (blue shading) in the frequency of easterlies over the entire North Atlantic, including the region of easterlies preceding Sandy's landfall (black contours in Fig. 2).

One of the most robust responses of climate models to increasing greenhouse gas concentrations is a poleward shift of the midlatitude jet streams (13, 14). The annual-mean jet shift by 2100 over the Western Atlantic (270° E–340° E) is poleward in all but three of the CMIP5 models (right-most dot in Fig. 3); however, the magnitude of the shift is seasonally dependent. The multimodel mean shows the largest poleward jet shift in

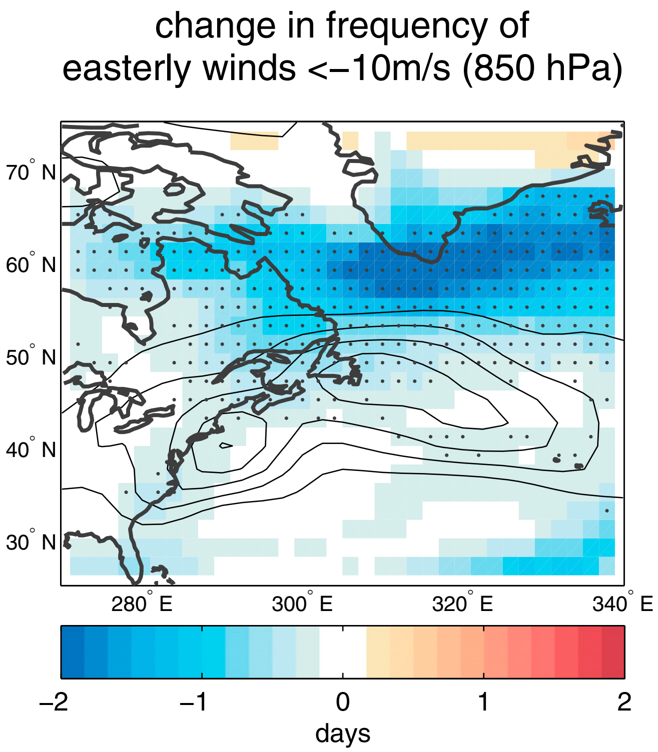

Fig. 2. The CMIP5 multimodel mean change in the ASO frequency of easterlies <−10 m/s at 850 hPa between the Historical (1980–2004) and RCP8.5 (2076–2099) CMIP5 climate scenarios. Stippling denotes locations where at least 80% of the models agree on the sign of the change. Black contours depict the average easterlies on October 27–29, 2012 contoured in increments of −5 m/s.

September–November, implying a more positive NAO state of the Atlantic circulation during the most active hurricane season. This is opposite to the equatorward-shifted jet (negative NAO state) during Sandy. A poleward-shifted jet implies stronger westerlies at higher latitudes: the projected decrease in the frequency of easterlies south of Greenland (Fig. 2) is in part due to the poleward jet shift.

In addition to the shift of the mean winds, the prevalence for easterlies is also influenced by persistence of weather patterns in the region. Consistent with fewer easterlies and a more poleward jet, the CMIP5 models also project a decrease in ASO blocking frequency by 2100 over the Western Atlantic basin (270° E–340° E; 35° N–90° N) (Fig. 4*A*). Of the 22 CMIP5 models, 17 predict a decrease in blocking frequency, and this supports the findings of Dunn-Sigouin and Son (15), who found a similar decrease using a different blocking detection method, demonstrating that the response is not dependent on methodology. Furthermore, the majority of the CMIP3 models also projected a blocking decrease over the region (16), demonstrating a robust signal across a broad range of models. Most climate models underestimate present-day blocking frequency over the Atlantic (17), and the same is true for the CMIP5 models (see refs. 15 and 18 for detailed discussions), although the biases are smallest in the warm months (15, 17). Although model biases necessarily reduce our confidence, the essential result is that the best models available offer no support for the conclusion that blocking frequency or westward steering will increase in the future.

Together with the decrease in blocking frequency, the CMIP5 models project a decrease in the number of cyclonic wave-breaking events over the Western Atlantic (Fig. 4*B*). A decrease in cyclonic wave breaking is consistent with fewer blocking anticyclones and less-frequent easterlies. All of these indicate the decreasing probability of a steering flow oriented toward the coast. Barnes and Polvani (13) present a dynamical explanation for the projected decrease in high-latitude, cyclonic Rossby wave breaking; they show that cyclonic wave-breaking frequencies will decrease in both hemispheres with climate warming and that this decrease is tightly coupled to the poleward shifts of the jets.

In addition to their steering influence, Rossby wave-breaking events are also linked to the extratropical transitions of tropical cyclones, whereby cyclones that begin their transition in the vicinity of a cyclonically breaking Rossby wave (and the associated negatively tilted trough) reintensify more than those that begin their transition near an anticyclonically breaking wave (12, 19). All else being equal, the projected future decrease in cyclonic wave-breaking events, therefore, suggests a decrease in the intensification of extratropically transitioning cyclones.

All of these results address only the future changes in the large-scale flow conditions leading to anomalous hurricane tracks, such as Sandy's. These conditions will influence the probability of Sandy-like events to the extent that the probability of a tropical cyclone (or hybrid, posttropical cyclone) moving into position to be steered onshore in easterly flow remains similar to what it is today; this, in turn, is related to the overall tropical cyclone frequency in the Atlantic basin. Recent studies disagree on whether Atlantic hurricane frequencies will increase or decrease as the climate warms (20–22), and little work has been done to date on how extratropical transition frequency may also respond, it being a function of both hurricane frequency trends and the local and global environment under which it transitions. Thus, it remains uncertain how the frequency of extratropical transitioning storms will change in the future.

Finally, recent studies have suggested that accelerated warming over the Arctic (Arctic Amplification) since the mid-1990s has contributed to a slow-down of the Atlantic jet stream and increased frequencies in slow-moving, large-scale Rossby wave patterns, and that these waves are responsible for extreme weather over the United States (23–25). In particular, such a link has been used to attribute the westward steering and landfall of Sandy in part to the Arctic Amplification (26). Our analysis indicates that the proposed link between Arctic Amplification and the westward steering of tropical cyclones does not seem to be supported by the CMIP5 simulations: all models project some

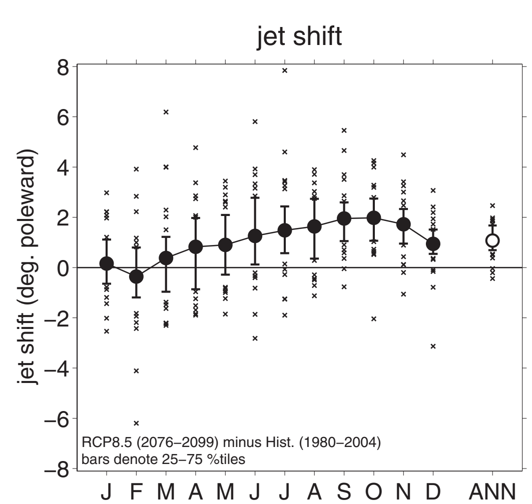

Fig. 3. The CMIP5 multimodel mean jet shift as a function of month between the Historical (1980–2004) and RCP8.5 (1976–2099) climate scenarios. The vertical bars denote the 25th to 75th percentile range, and the crosses denote values outside of that range.

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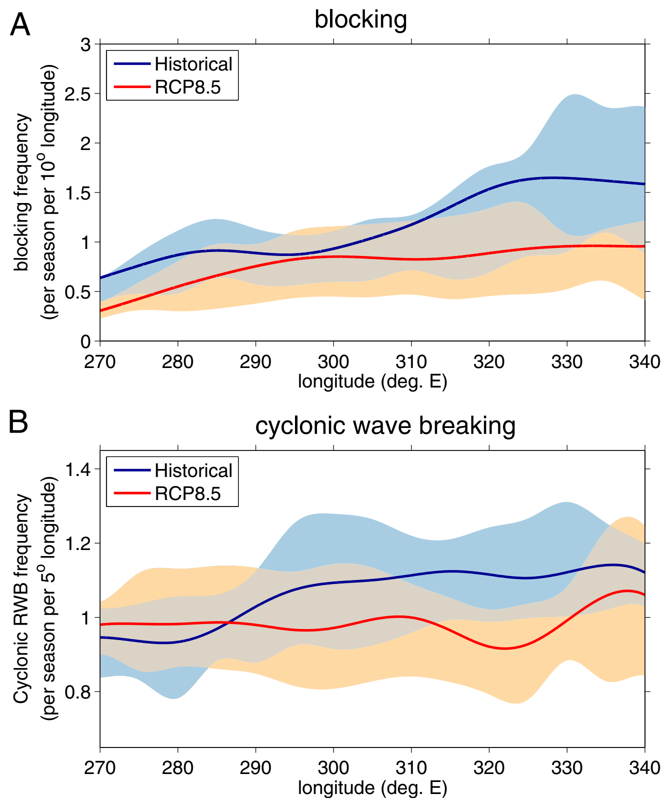

Fig. 4. CMIP5 ASO (*A*) blocking frequency and (*B*) cyclonic wave-breaking onset frequency poleward of 30° N as a function of longitude for the Historical (1980–2004) and RCP8.5 (2076–2099) climate scenarios. Lines denote the CMIP5 multimodel mean, and shading denotes the 25th-75th percentile range among the models. All lines have been smoothed (*Materials and Methods*).

degree of Arctic Amplification, although most also project a decrease in the conditions responsible for the westward steering, namely easterlies and cyclonic wave breaking.

Materials and Methods

Hurricane Tracks and Reanalysis Data. Observed fields of zonal wind, geopotential height, and absolute vorticity were obtained from the NCEP/NCAR Reanalysis (www.esrl.noaa.gov/psd). The tropical cyclone tracks are the HURDAT2 Best Track Data obtained from the National Weather Service National Hurricane Center (www.nhc.noaa.gov/pastall.shtml).

CMIP5 Scenarios and Model Data. We used model output from the fifth phase of the CMIP5 archive. Specifically, we analyzed monthly-mean zonal wind (26 models) and daily zonal and meridional wind (22 models) from two forcing scenarios: Historical (1980–2000) and RCP8.5 (2076–2099). The CMIP5 models used in this analysis are given in Table S1. The RCP8.5 scenario corresponds to an extreme warming scenario whereby transient emissions throughout the 21st century induce a top of atmosphere radiative forcing of 8.5 W/m^2 by 2100. Additional details about the CMIP5 experiments can be found in ref. 27. We use only one ensemble per model experiment here for consistency.

Model Field Interpolation. Model zonal wind fields were interpolated to a 2° × 2° grid before the calculation of the frequency and duration of easterlies (Fig. 2).

Jet Definition. The latitude of the jet over the Western Atlantic basin is defined as the latitude of maximum sector-mean, 700–850 hPa (vertically averaged) zonal winds (as in, e.g., refs. 14, 28, and 29). The lower-level winds are used to distinguish the eddy-driven jet from the subtropical jet, which has easterlies at the surface and westerlies aloft. The jet latitude is calculated by interpolating to a fine grid, fitting a quadratic, and finding the latitude of the peak. The jet latitude for each month is calculated separately, and then the average of the monthly positions defines the jet latitude over a specific time period. Analysis performed over other pressure levels is located in *SI Text* and shown in Fig. S2.

Figure Preparation. The frequency curves in Fig. 4 were created by binning the data into 5° longitude increments and then smoothing the multimodel mean curves with a forward and backward 1-2-1 nonrecursive filter.

Blocking Algorithm. We use the one-dimensional blocking algorithm of ref. 16, which identifies blocking regimes using the 500-hPa zonal wind field. Briefly, blocked longitudes are identified on the zonal wind field following Scaife et al. (17), whereby a block is a reversal of the geopotential height gradient and we assume geostrophic balance. Blocked longitudes are grouped in time and space to form a single blocking regime. All parameters and methods are identical to those of ref. 16, except we smooth the eddy-kinetic energy field (used to define the seasonally varying storm track position) using a 7-d box-average filter, and results are not sensitive to this difference. In addition, we interpolate all model data to the same grid before calculation of the central blocking latitude and blocked regimes. The daily position of a block is defined as the mean longitude of the blocking regime that day. Note that this definition gives zonally larger blocks the same weight as zonally smaller blocks, so that the frequency is a measure of the number of days with a block centered at that longitude.

Wave-Breaking Algorithm. The wave-breaking algorithm used here is identical to that of refs. 13 and 30, whereby overturning contours of absolute vorticity on the 250-hPa surface define a wave-breaking event. As for the blocking algorithm, overturning contours for the same event are grouped together in time and in space. Here, we define the location of the wave-breaking event as the mean longitude and latitude of the overturning contours on the onset day. Once again, this definition gives zonally larger wave-breaking events the same weight as zonally smaller events, so that the frequency is a measure of the number of days with the onset of a wave-breaking event centered at that longitude.

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